Response to RC3 by Reviewer 1:

We would like to thank the reviewer for performing a thorough review and for the many helpful suggestions to improve our manuscript.

Below, we respond to each of the review comments. For the sake of clarity, the review comments are given in blue italics and our response is printed in normal font. Changes to the manuscript are printed in green.

This work is a great addition to the currently available angular dependent LER products that have considered surface BRDF effects based on the LER concept. It provides important improvements to the author's previous LER climatology product based on GOME-2 observations, which include directional LER (DLER) at as many as 26 wavelengths from 328 to 772 nm. It fits well to the scope of AMT and should be considered publishing after addressing the following issues.

1. Although bidirectional reflectance distribution function (BRDF) mathematically describes the scattering of a parallel beam of incident light from one direction in the hemisphere into another direction in the hemisphere, the BRDF itself, as a ratio of infinitesimals, is a derivative with "instantaneous" [in angle] values that can never be measured directly, as stated in Nicodemus et al. (1977).

Therefore, it seems more proper to use BRF or simply reflectance in many places throughout the manuscript when referring to directional reflectance datasets. BRF (Bidirectional Reflectance Factor) is defined as the ratio of the radiant flux reflected by a surface to that reflected into the same reflected-beam geometry by an ideal (lossless) and diffuse (Lambertian) standard surface, irradiated under the same conditions.

So in remote sensing community, BRF is commonly used to describe the reflectance factor calculated from either ground measurements or satellite observations that have finite field-of-view (FOV). The authors can refer to Schaepman-Strub et al., (2006) for more details regarding use of BRDF and BRF.

The suggestion here is to only keep BRDF before 'model', 'parameter', 'product', 'database' etc (i.e., only use it as an adjective) and replace BRDF with BRF in other places when referring to directional data set itself, such as at line 9, 11, 14 in page 1, as well as many instances in the rest of the manuscript.

The reviewer is right in principle, but for the clarity of the paper we choose to use only BRDF and not BRF as well. We have, however, checked the manuscript for the use of the term "BRDF" and now use it as an adjective instead or have replaced it with "reflectance" for a number of cases where this is more appropriate. For instance, the lines 9–14 on page 1 of the manuscript now read:

" The relation between DLER and BRDF surface reflectance is studied using radiative transfer simulations. For the shorter wavelengths ($\lambda < 500$ nm), there are significant differences between the two. For instance, at 463 nm the difference can go up to 6% at 30° solar zenith angle. The study also shows that, although DLER and BRDF surface reflectances are different properties, they are comparable for the longer wavelengths ($\lambda > 500$ nm). Based on this outcome, the GOME-2 surface DLER is compared with MODIS surface BRDF data from MODIS band 1 (centred around 645 nm), using both case studies and global comparisons. The conclusion of this validation is that the GOME-2 DLER compares well to MODIS BRDF data . . . "

In section 1 and also in section 2.2 we now also refer to the paper by Schaepman-Strub et al. [2006].

2. It seems not proper by calling LER (defined in Eq.2) as albedo (see line 21, page 3) because albedo is defined as the ratio of the radiant flux reflected into the whole upper hemisphere (i.e., the integal from all viewing angles) to the incident radiant flux. In other words, albedo is independent of viewing directions, but LER does for a non-Lambertian surface. That is the physical basis for DLER in this study, GE_LER (Loyola et al., 2020) and GLER (Vasilkov et al., 2017). Also as shown in Eq.3, LER has the same unit as R.

We agree that LER should not be called an albedo, however, in the derivation leading up to equation (3), the term "albedo" is only used for the surface albedo, which is explicitly defined to be independent on the viewing directions. In equation (2), the LER is not defined yet.

We have changed the last sentences of section 2.1 in the following way:

" Both parameters $R_\lambda^{\rm obs}$ and R_λ^0 depend on μ, μ_0, and $\phi - \phi_0$, so, in general, so does $A_{\rm s}$. When clear-sky conditions apply, the parameter $A_{\rm s}$ is the Lambertian-equivalent reflectivity (LER) of the surface. "

This avoids referring to the LER as an albedo. Additionally, we have searched the entire manuscript for the words "surface albedo" and have replaced these with "surface reflectance" where appropriate.

3. The authors should mention in the figure caption that Fig.1b only applies to land surfaces because reflection from a non-Lambertian surface, in general, could have another peak in the forward scattering direction, i.e., specular (mirror) reflection over snow/ice or water surfaces (so-called sunglint) in addtion to the hot spot peak (retroreflection) over rough surfaces like vegetation due to shadow hiding.

The caption mentions that the surface reflection distribution in Figure 1b is representative for vegetation. To avoid confusion, we changed the caption of Figure 1. The caption now reads:

" Left: Illustration of the principle of Lambertian (isotropic) surface reflection. Right: Surface reflection distribution with a retroreflection lobe, representative for land surfaces covered by vegetation. In the DLER retrieval code, the orbit swath is divided into five viewing angle ranges and for each segment the surface LER is determined in the usual way. "

4. The authors should provide reference(s) to justify the use of a parabolic function to simulate directionality of surface reflection for vegetated surfaces as shown in Eq.5. There have been many publications from BRDF modeling community in land remote sesing that demonstrated such parabolic function only applies to non-vegetated surfaces such as desert or bare soil. That's why in MODIS BRDF products, a linear combination of different kernels is used to describible surface drectional reflection in general as described by Eq.6.

A second-order polynomial can indeed not catch all characteristics for all geometries and for all surface types. In particular, the "hot spot" will not be represented well for all geometries. However, compared to the standard non-directional approach the use of second-order polynomial is already quite an improvement.

We have experimented with a higher number of bins, to get a better feel of the variability of the DLER. The higher number of bins goes at the expense of the reliability of the LER in the bins, because of a higher probability that a good cloud-free value can be found. For some regions, however, this does work and we can analyse the variability of the DLER.

We did indeed see that the parabolic shape works very well for desert surfaces. For vegetation the parabolic function seemed to work well as well. Note that the regime of the viewing and solar angles that are involved is representative for the GOME-2 orbit, and therefore constitutes a subset of the range of angles supported by MODIS BRDF. Also, the GOME-2 orbit swath is less wide than that of the MODIS instruments. It may be so that the geometries involved for GOME-2 are more forgiving when it comes to modelling the directionality of the surface reflection with a simple parabolic function as we did.

In section 5, item 5, we now mention more clearly that the DLER is an approximation:

" 5. The database now offers directionally dependent surface LER (DLER). This means that the anisotropy of the surface reflection, often called the BRDF effect, is contained in (and described by) the DLER database. The provided DLER is an approximation in the sense that the second-order polynomial approach presented in section 2.2 in combination with the 5 angular bins of about 20 degrees each will not be able to catch the angular variability of the DLER for all surface types and situations. In particular, for vegetated surfaces the "hot spot" will not in all circumstances and geometries be represented well. Also, the DLER database is in principle representative only for the geometry of the GOME-2 orbit. "

5. The title of section 3.1 should be changed to 'MODIS BRDF model'.

Agreed, we have changed the title of section 3.1 to "MODIS BRDF model":

" 3.1 MODIS BRDF model "

6. Though I believe DLER is derived from the real GOME-2 measurements as mentioned in the 2nd paragraph (lines 9-14, page 4) of section 2.2, it also says DLER product is based on simulated TOA reflectances with DAK (line 23, page 6), That would create some confusion for readers and should be clarified.

DLER is indeed derived from the real GOME-2 measurements. However, in section 3.2, the DLER database is not described. Here the model calculations of DLER and MODIS BRDF are described.

To avoid confusion, we have changed the text in the following way:

" Next, the simulated surface DLER is calculated from the simulated TOA reflectances using a similar setup as the one described in Sect. 2. "

7. Since real GOME-2 observations are used to derive DLER, it is not clear how the aerosol and cloud contaminated data is removed and the data screening criteria used. How data gaps (due to aerosol and/or cloud contaminations) are handled? All these need to be addressed in the manuscript.

Absorbing aerosol is removed by using the Absorbing Aerosol Index (AAI) to filter out absorbing aerosol. However, we do not actively apply a correction for background scattering aerosols, and these are in principle included in the DLER database, even though the algorithm is focused on the minimum scene reflectivities. Cloud screening is performed in a statistical manner, without the use of external cloud information, as described in section 5 of the manuscript (lines 6–10). Post-processing steps are needed to address gaps and residual cloud contamination. All of this is described extensively in our previous paper [Tilstra et al., 2017].

We now mention these steps briefly in the updated version of the manuscript, by referring to our previous paper. The text in section 5 has been changed in the following way:

“ . . . the observed scene LER values of a specific month (but from all available years) are distributed onto a latitude/longitude grid which represents the Earth’s surface for that specific calendar month. In this step, observations containing absorbing aerosols are filtered out using the Absorbing Aerosol Index (AAI). For each grid cell the distribution of scene LER values is then analysed statistically to find the cloud-free observations. This is done in two ways . . .

. . . After these steps, post-processing corrections are performed that take of issues such as gaps and residual cloud contamination. The above steps and procedures have all been described extensively in Tilstra et al. [2017]. There are . . . ”

8. It looks like DLER product only has five viewing direction bins since the data is sorted out through five sub-containers (see line 12, page 4). What are the exact angular widths for these five bins, any justification that these five anglular bins can adquently describe the angular distribution of GOME-2 measurements? What is the angular resolution in the GOME-2 x-track scan positions and is that the basis for selecting the five view angle bins? All these need to be deliberated a little more.

Since this is not a full consideration of BRDF effects but a rough approximation, it should be said so in item 5 of page 10 (lines 22-23).

Although this approximation may work for not too large SZAs where the angular width of the hot spot is pretty broad. However, when SZA is high (e.g., larger than 45 deg), the hot spot width becomes very narrow. In such situation if GOME-2 viewing angle falls into the hot spot region, the peak will be smoothed out by the large angular bin as shown in figure 1b, resulting in much smaller DLER value. Same is true for the sunglint effect over ocean should this five viewing angle scheme be applied to water surfaces,

The GOME-2 instrument has a swath width of 1920 km. In the normal operation of the instrument this swath is made up of 24 pixels from east to west (in the forward scan of the instrument). The viewing zenith angle goes up to 55 degrees at the swath edges. The size of the 5 angular bins is about 20 degrees in viewing angle.

The decision to use only 5 bins (and not more) was based on the fact that the algorithm needs enough observations to be able to find the necessary cloud-free observations. If we decide to use more bins, then there will be less data contained in each bin, decreasing the chances of finding cloud-free observations.

It is certainly true that the DLER database provides an approximation of the directionality. This is now mentioned explicitly in the manuscript, in item number 5 of section 5, as suggested:

“ 5. The database now offers directionally dependent surface LER (DLER). This means that the anisotropy of the surface reflection, often called the BRDF effect, is contained in (and described by) the DLER database. The provided DLER is an approximation in the sense that the second-order polynomial approach presented in section 2.2 in combination with the 5 angular bins of about 20 degrees each will not be able to catch the angular variability of the DLER for all surface types and situations. In particular, for vegetated surfaces the “hot spot” will not in all circumstances and geometries be represented well. Also, the DLER database is in principle representative only for the geometry of the GOME-2 orbit. ”

As for the sun glint effect over the oceans, the climatology does not try to describe the directionality of the surface reflectivity over water surfaces. Over the oceans the directionality is not recorded. That is, the polynomial coefficients c_0, c_1, and c_2 are zero over the oceans. This is explained in section 2.2 of the manuscript.

9. Fig.7 shows results at 772 nm. Readers may also be interesed to see results for short wavelengths (e.g., 363, 380, 340 or shorter) since some of the short wavelengths in Table 1 are widely used in trace gas retrieval based on UV/VIS data such as ozone, NO2, aerosol via aersol index and clouds via O2-O2 or rotational Raman scattering algorithm.

We had selected 772 nm because for this wavelength the largest anisotropy is to be expected. Another reason for selecting 772-nm wavelength band is because it is relevant for cloud and aerosol retrieval using the O_2-A band. In Figure 1 of this AC we present, as an example, the result for 463 nm.

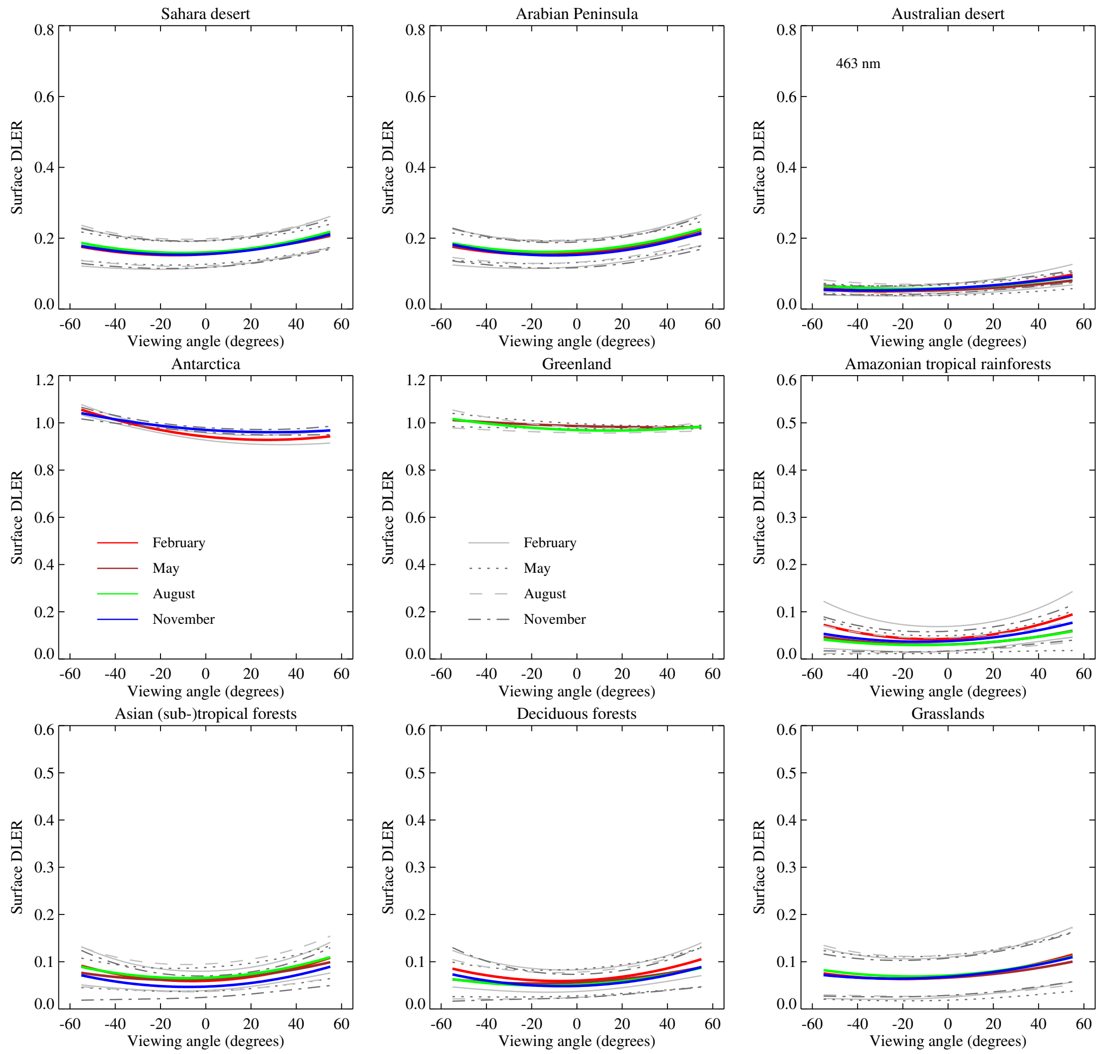

Figure 1: Similar to Figure 7 of the manuscript, but now for 463 nm.

We have decided to add results for other wavelength bands as part of the Supplement. The wavelength bands that were added to the Supplement are: 670, 463, and 380 nm.

10. For Figs. 8-9, DLER from 645 nm is compared with MODIS band 1. Can the authors show comparisons with the shortest wavelength in MCD43C2 product like band 3 (centered at 470 nm)? Though the difference *would be larger as expected, readers may be interested to see how DLER and MODIS BRF follow with each other in angular distributions.*

We have compared DLER to the MODIS BRDF product for three wavelengths:

- 640 nm – MODIS band 1 (around 645 nm)
- 555 nm – MODIS band 4 (around 555 nm)
- 463 nm – MODIS band 3 (around 469 nm)

The results are shown in Figures 2 and 3 of this AC.

Looking at the plots in Figure 2 of this AC, there seems to be an offset for the shortest wavelength. A possible explanation could be the background aerosol scattering, which is still present to some degree in the GOME-2 surface DLER database because there is no active filtering for scattering aerosol in the retrieval code.

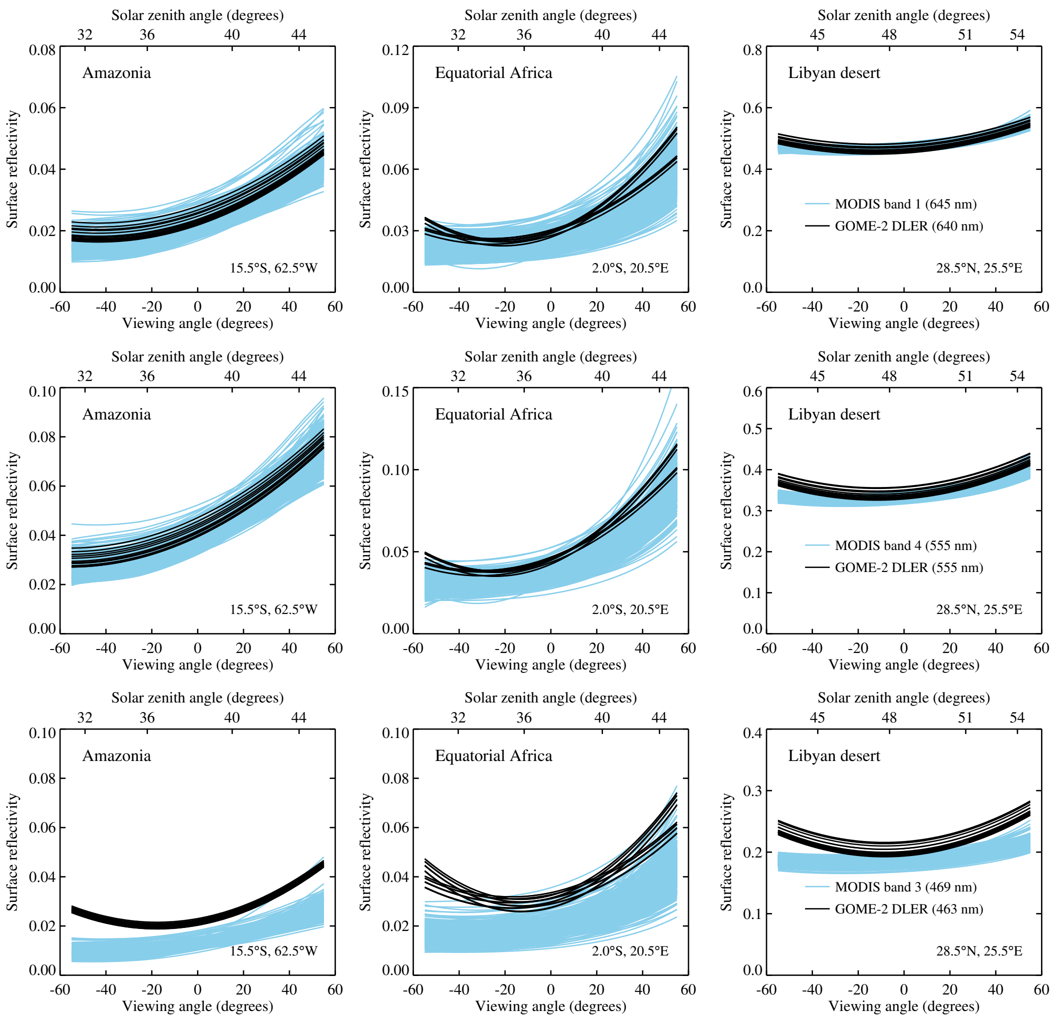

Figure 2: Case studies for 640, 555, and 463 nm. The surface reflectivity, originating either from GOME-2 DLER (in black) or MODIS BRDF (in blue), is presented on the vertical axis, plotted as a function of the viewing angle. These figures are similar to Figure 8 of the manuscript.

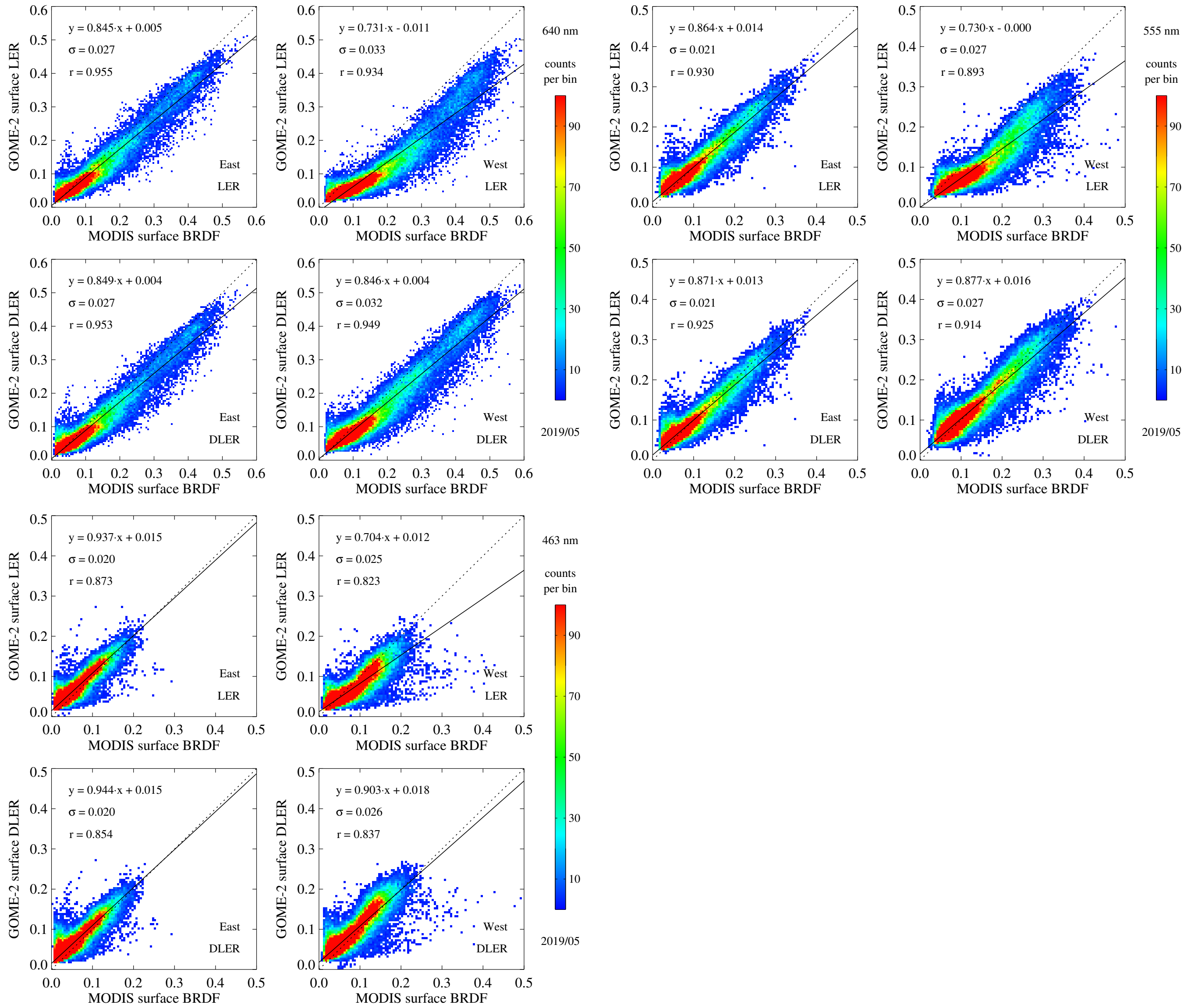

Figure 3: Pixel-to-pixel comparisons for 640, 555, and 463 nm. These are global comparisons between GOME-2 surface (D)LER and MODIS surface BRDF for the period 10–19 May 2019. Top row of each figure: GOME-2 non-directional surface LER versus MODIS surface BRDF, for eastern and western sides of the orbit swath (see main text). Bottom row of each figure: GOME-2 directional surface DLER versus MODIS surface BRDF. These figures are similar to Figure 9 of the manuscript.

We have added this comment to the discussion in section 7.1 of the manuscript:

“ The lower performance at the most extreme viewing angles could be a result of the fact that in the parabolic fitting procedure explained in Sect. 2.2 inaccuracies are not corrected at the swath ends, but they are in the centre of the swath. Also, the parameterisation used for the DLER is a second-order polynomial, so higher-order dependencies are not described well. Another explanation could be background aerosol scattering. There is no explicit filtering or correction for aerosol scattering in the retrieval code. Aerosol scattering would have the largest impact at the extreme viewing angles. ”

We have decided to add the additional plots for the other wavelength bands to the Supplement.

References:

Schaepman-Strub, G., Schaepman, M. E., Painter, T. H., Dangel, S., and Martonchik, J. V.: Reflectance quantities in optical remote sensing–definitions and case studies, Remote Sens. Environ., 103, 27–42, doi:10.1016/j.rse.2006.03.002, 2006.

Tilstra, L. G., Tuinder, O. N. E., Wang, P., and Stammes, P.: Surface reflectivity climatologies from UV to NIR determined from Earth observations by GOME-2 and SCIAMACHY, J. Geophys. Res.-Atmos., 122, 4084–4111, doi:10.1002/2016JD025940, 2017.